Prediction of the structural effects of expansive reactions on a concrete structure in a marine environment

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Abstract

The high potential of the residual expansion due to Delayed Ettringite Formation (DEF) identified in the diagnostic tests performed to a concrete quay wall motivated the study of its structural effects.

The structural analysis performed considers the earth and water pressure on the wall, the environmental thermal variations and the time-dependent behaviour of creep and swelling due to DEF. For this purpose, a section of the wall was modelled by three-dimensional finite elements, including the reinforcement steel bars through bar elements. The calculation of free swelling action took into account the laboratory results obtained as well as the annual thermal variations of the environmental nature.

The main aim of this work is to present the modelling of this structure in order to understand and predict the structural performance in the next years, providing relevant information for the adoption of preventive measures.

Keywords: *concrete; delayed ettringite formation (DEF); seaport; structural analysis; structural effects*

1.   INTRODUCTION

Delayed ettringite formation (DEF), also known as internal sulfate reaction (ISR) designate the phenomenon heat-induced internal sulfate attack. As the name suggests, the phenomenon may be defined as the formation of ettringite in a cementitious material by a process that starts after hardening is mostly complete and in which the sulfate comes from either cement or gypsum contaminated aggregates [1] [2]. It normally occurs in concrete that has experienced temperatures above 70 ºC for a sufficient length of time during early cement hydration, and results in expansion and cracking when the concrete returns to ordinary temperature and is subsequently exposed to moist conditions, intermittently or permanently [1] [2]. Depending on the chemical and environmental conditions, the DEF induced damage can be of various degrees: from superficial cracks and concrete swelling to breaking of reinforcing bars, which can lead to the loss of load bearing capacity [3]. Since the actual temperature above which deleterious DEF is likely to occur varies with several factors, *e.g.* the concrete composition/constituents, there is still no global consensus on a safe temperature limit; therefore, some countries consider in their regulations a lower temperature limit, for instance 65 ºC.

Today, concrete can be formulated free from deleterious DEF, yet many new structures exhibit DEF. This is because preventive measures are not always feasible or applied in practice, and consequently temperatures above 70 ºC are obtained during concrete cure. For example, to reduce construction costs, concrete structures must be built in a very short period, implying that often concrete has a cement content higher than necessary just to obtain higher strengths at early ages; concrete might have to be placed during hot periods; concrete is placed in larger volumes.

The high potential of the residual expansion due to DEF identified in the diagnostic tests performed to the concrete of a seaport motivated the study of its structural effects. This paper presents the time-dependent analysis of this structure, affected by creep and DEF effects, in order to predict the structural performance in the next years, providing relevant information for the adoption of mitigation measures.

2. MATERIALS AND ACTIONS MODELS

2.1 Time-dependent properties of concrete

The time-dependent behaviour of concrete has a relevant impact on large structures' performance. Stresses, strains and displacements of reinforced concrete structures vary continuously with time due to creep and shrinkage effects. The analysis of the time-dependent effects in concrete structures must consider the time variation of modulus of elasticity and creep and shrinkage properties of concrete.

When the information of specific tests is not available, a prediction model is used to obtain an analytical behaviour of the concrete structure. In the presented study, for the viscoelastic time-dependent analysis, the time behaviour of the modulus of elasticity and creep of the concrete are considered as defined by Eurocode 2 [4].

Therefore, the variation of modulus of elasticity with time can be estimated by:

$$E_t = E_{28} \times \left(exp\left\{ s\left[1 - \left(28/t \right)^{1/2} \right] \right\} \right)^{0.3} \tag{1}$$

where E_t is the value at an age of t days, E_{28} is the value determined at the age of 28 days and s is a coefficient which depends on the type of cement.

The creep deformation of concrete $\varepsilon_{cc}(\infty, t_0)$ at long term (t = ∞) for a constant compressive stress σ_c applied at the concrete age t_0, is given by:

$$\varepsilon_{cc}(\infty, t_0) = \varphi(\infty, t_0) \times \left(\sigma_0/E_0 \right) \tag{2}$$

The creep coefficient $\varphi(t, t_0)$ can be calculated from:

$$\varphi(t, t_0) = \varphi_0 \times [(t - t_0)/(\beta_H + t - t_0)]^{0.3} \tag{3}$$

where φ_0 is the notional creep coefficient, β_H is a coefficient depending on the relative humidity and the notional member size (h_0).

2.2 Thermal and hygrometric actions

The free swelling evolution depends on thermal and hygrometric histories of the structure, which is a function of environmental conditions resulting from their exposure.

The thermal analysis is a problem of heat conduction, of which the solution implies the knowledge of the thermal conductibility of concrete and of the thermal variation of air and water on exposed surfaces, as well as the solar radiation effects. For concrete structures the thermal expansion coefficient is taken $\alpha = 1 \times 10^{-5}/°C$ and the thermal diffusivity is $h^2 = 0.095\ m^2$ per day.

The law of heat conduction, also known as Fourier's law, states that the rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat flows. Using finite element method, the temperature history on each point of the structure during each time interval Δt of the period considered can be defined.

The spatial and temporal hygrometric distribution can be similarly computed, based on the representative curve of the environmental humidity. The moisture diffusivity for concrete is $h^2 = 0.00068\ m^2$ per day.

2.3 Swelling action

The progress of swelling reactions depends on the several factors: the chemical process that depends on the concrete composition; temperature; moisture; stress field and time.

The damage-chemo-viscoelastic model is a nonlinear structural model that includes a module to simulate the macroscopic swelling effects by means of an imposed deformation history. The evaluation throughout the time of these imposed deformations, considers intrinsic factors of concrete (aggregate type and size, cement and alkali content) and the environmental variations of temperature and moisture [5].

The free swelling curve is common with an sigmoid configuration (Figure 2.1), being characterised by a latency time (τ_L), the moment when the reaction accelerates by increasing the diffusion within the material due to micro-cracking, and τ_C, the characteristic time, which pertains to the attenuation phase of the phenomenon [7] - [11]. The swelling parameters $\tau_L, \tau_C, \varepsilon(\infty)$ can be directly obtained from free swelling tests, carried out with concrete specimens immersed in water at 20 ºC [12].
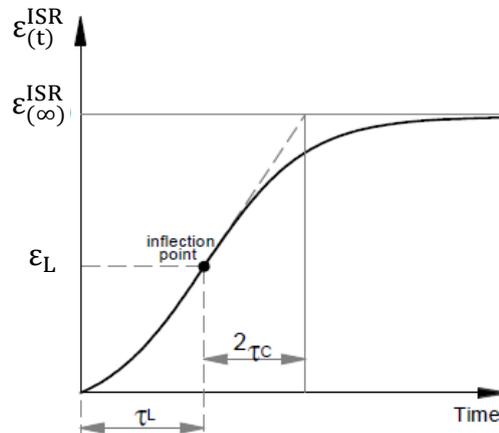
Figure 2.1: Free swelling curve

The influence of the temperature variation during the swelling process, in the structure, is considered using the following equations:

$$\tau_C(T) = \tau_C(T_0)e^{\left[U_C\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]} \tag{4}$$

$$\tau_L(T) = \tau_L(T_0)e^{\left[U_L\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]} \tag{5}$$

where U_C is the activation energy associated to the characteristic time, U_L is the activation energy corresponding to the latency time, T_0 is the temperature of the reference free swelling test and T is the temperature in the time interval, Δt, considered in the discretisation established for the analysis in the time domain.

The presence of moisture inside the concrete is a fundamental condition in the appearance and development of swelling reactions. Laboratorial tests on hardened concrete specimens subject to sulfate reactions show that for relative humidity less than 90% there are no expansions in the concrete. However, when the relative humidity is over 95% [10], the expansions increase. So the governing law to take into account the influence of moisture on the evolution of the swelling process can be expressed, in case of sulfate reactions, by equation (6) with m equal to 40 [10].

$$\varepsilon^{H_r} = H_r^m \varepsilon^{100\%} \tag{6}$$

2.4   Structural model

The structural analysis, considering the time dependent behaviours of the swelling development and the creep of the concrete, is performed by the finite element method, adopting a displacement formulation, through an incremental procedure of application of loads that separates, at each time step, the instantaneous response from the delayed response [5],[6].

The instantaneous calculations consider the imposed deformations due to the swelling process, the water and earth pressure loads and the thermal variations; and an iterative procedure is used to take into account the dependency of the swelling action on the stress field. In the delayed calculation, the concrete time-dependent behaviour is considered using nodal forces equivalent to the effect of the load history.

For each time step, the equation is solved in order to evaluate the incremental displacements, the stiffness matrix being updated in each time step.

The structural model considers quadratic hexahedral elements with twenty-nodes to represent the concrete and truss elements for modelling reinforcing steel bars effects. To evaluate accurately the differential swelling from the external surfaces to the core of the concrete, influenced by the variations in temperature and moisture inside the concrete, quadratic shape functions, three Gauss points in each direction, a lattice of 27 Gauss points per element, has to be used. These allows a detailed analysis along the thickness and distinguish the zone confined by the reinforcement of the zone not confined.

3. CASE STUDY - SEAPORT

3.1 Description

The quay structure is a reinforced concrete structure and consists of front wall and capping beam. The front wall is a long structure formed of interlocked panels with 3 m wide. The interlocked panels, with 29 m height and 1,2 m thick, are anchored through a long steel tie rod system anchored at the front wall, 2 m away from the top. The wall is heavily reinforced, especially in the seaside.

The concrete class applied in the front wall design is C35/45. For a ready mixed concrete there is used cement content of 385 kg/m^3. The water-cement ratio was less than 0,50. The steel class of the reinforcing bars is A500.

During the construction, some elements of the structure were subjected to high temperature conditions (76ºC were measured in inner part of the concrete element), which rose concerns about the risk of deleterious development of DEF in the concrete.

Because of that, a laboratory test campaign was carried out to confirm the existence of the phenomena in the concrete from the structure. When cores were extracted from the structure, no cracks were visible in the structure. The laboratories tests comprised not only the execution of residual DEF expansion tests on concrete specimens, but also chemical and mechanical tests on concrete specimens collected from several locations of the structure. In addition to the above, the test campaign also included the determination of the heat of hydration and the chemical analysis of the cement used in the structure. The preliminary results of the laboratory analysis and tests confirmed the presence of the DEF phenomenon in the concrete. The stiffness damage test showed that there was a great variability on the condition of the concrete sampled. From the results obtained in the residual expansion tests it was found the residual ISR residual reactivity varied considerably amongst the various sections of the structure. Despite that, all sections exhibited a relevant residual expansion potential. The likelihood of ASR occurrence was not assessed at the client request.

3.2 Time-dependent behaviour of the concrete

In the structural modelling developed for swelling analysis the modulus of elasticity and the rheological behaviour are defined by the EC2 (Figure 3.1), considering the modulus of elasticity of the concrete at the age of 28 days E_{28} = 33,5 GPa.
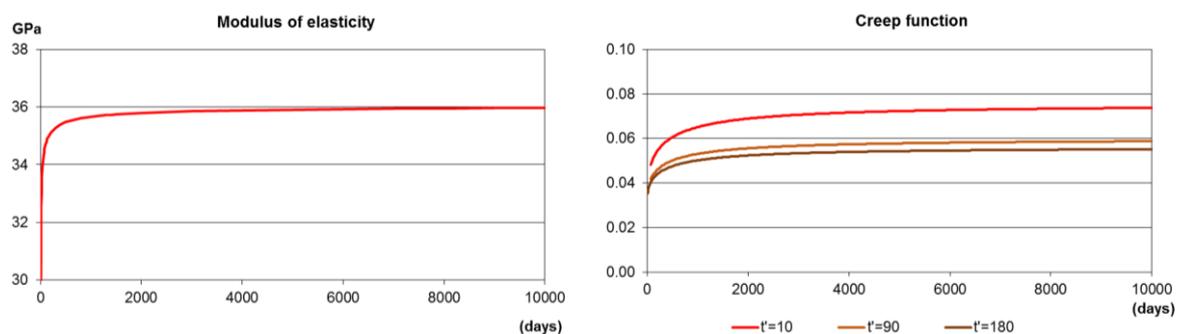

Figure 3.1: Evolution of the modulus of elasticity and creep function

3.3   Temperature conditions

As previously mentioned, the evolution of the free swelling depends on the concrete's temperature and hydrometric distribution, spatial and temporal.

The front wall intersects with three different environments: land, seawater and air. Based on the available information, the annual harmonic functions of the air (7) and coastal sea surface temperature (8) were achieved (Figure 3.2):

$$T_{air}(t) = 29,5 - 2,7 \times sin\left(\frac{t + 125}{365} \times 2\pi\right) \ \ (°C) \tag{7}$$

$$T_{sea}(t) = 27,2 - 1,6 \times sin\left(\frac{t + 135}{365} \times 2\pi\right) \ \ (°C) \tag{8}$$

It is considered that temperatures of the water decrease linearly with increasing in depth and at elevation -16,5 m the temperature follows the expression (9).

$$T_{-16.5}(t) = 24,2 - 0,75 \times sin\left(\frac{t + 135}{365} \times 2\pi\right) \ \ (°C) \tag{9}$$

Therefore, the spatial distribution of temperatures (temperature field) inside the panel were defined by the Fourier's law.
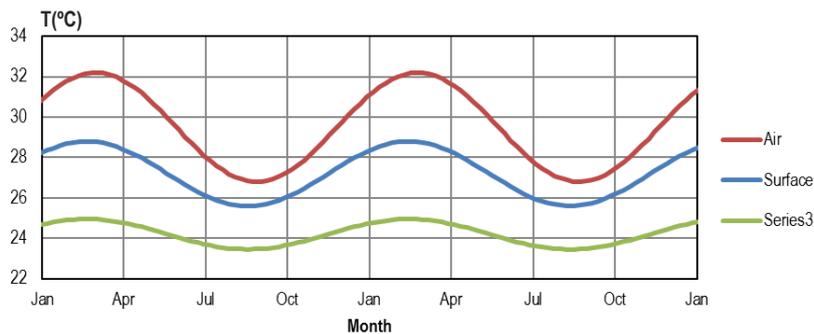

Figure 3.2: Thermal annual waves

3.4   Free swelling

The free swelling curves (Figure 3.3) were defined from the results of laboratory expansion and stiffness damage tests, which defined the expansive potential of the specimens obtained from the structure. The different expansion kinetics and magnitudes observed during the test, for the several specimens assessed, most likely derive from local variations in the structure of environmental conditions and concrete composition. The maximum expansion of the average free swelling in the specimen was of about 2200×10^{-6}.
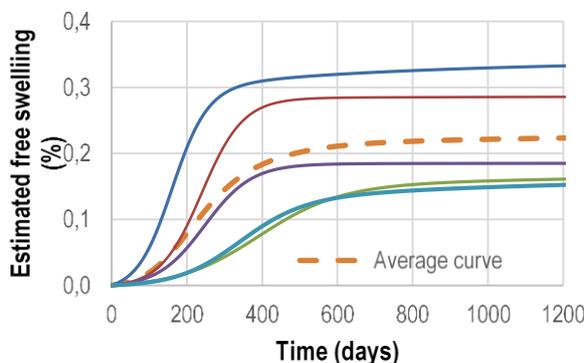

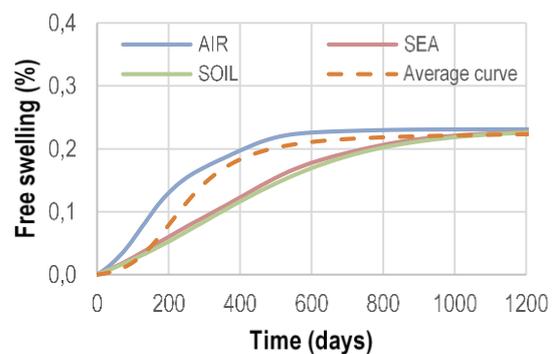Figure 3.3: Free swelling curve of the specimens

Figure 3.4: Free swelling inside the wall

Therefore, the average free swelling actions were estimated, considering the environmental conditions, namely the thermal actions. Since the wall is immersed practically all time throughout its height, the hydrometric conditions necessary for the development of expansive actions are satisfied. An isotropic free swelling was assumed.

In Figure 3.4 the free swelling evolution in three environmental conditions are presented. Since the air temperature is always higher than that of seawater, the expansion in the structural elements that are in contact with the air progresses faster. However, in all elements, the swelling process stabilizes after 4 or 5 years.

3.5   Water and earth pressure loads

As retaining wall structure in marine environment, the front wall works under earth pressure and hydrostatic pressure. The combination of the earth pressure considering the sea level and the corresponding values of axial force (N), shear force (Q) and bending moments (M) of the wall are shown in Figure 3.5.
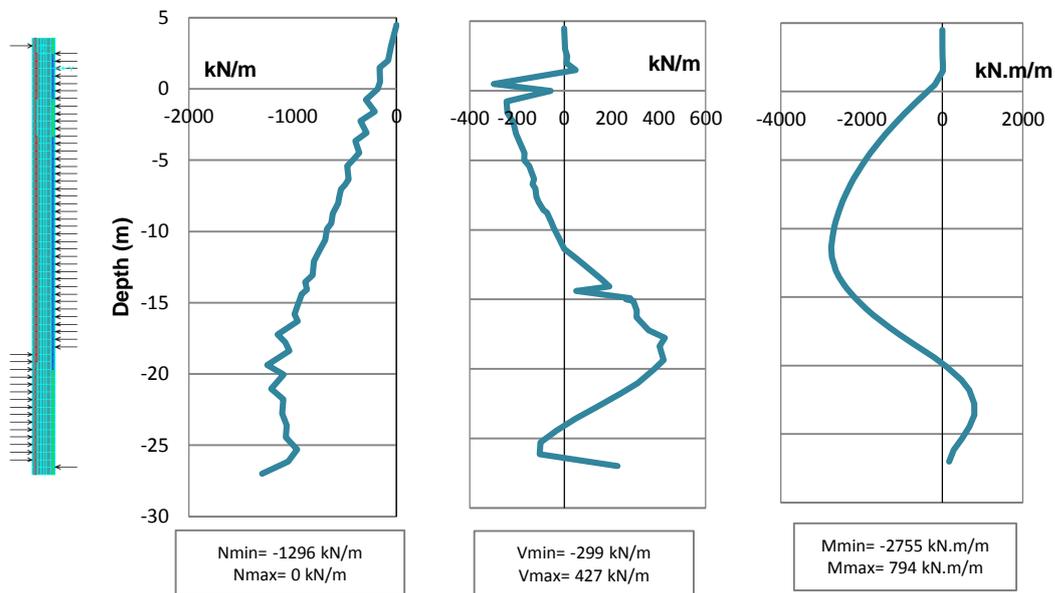

Figure 3.5: Water and earth pressure efforts

3.6   Structural element finite model

For the analysis of the swelling effect on the front wall a three-dimensional finite element model was developed. No cracking effects in concrete were considered in this first approach for structural analysis.
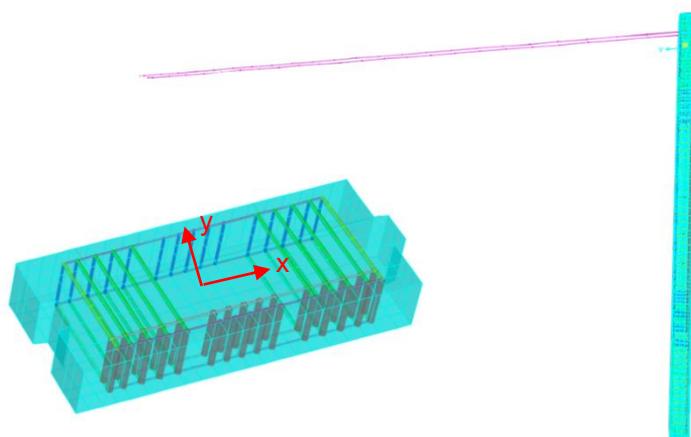

Figure 3.6: Finite element model of the panel

To evaluate accurately the differential swelling along the thickness of the wall, and considering the distribution of the reinforcement bars, there are used hexahedral elements with small section in the plan (between 0,012 m² and 0,041 m²) by 0,5 m height. The reinforcing bars are modelled by truss elements, distributed at the vertices of the hexahedral elements. The cross section of the truss elements varies between 0,0002 m² (φ16) and 0,0024 m² (3φ32). In this way, the panel was modelled by 9744 20-node hexahedral elements and 8308 truss elements (Figure 3.6).

A temporal discretization of the main actions (thermal action, swelling) was carried out, with the main objective of evaluating and predicting the structural effect of the ISR. The 7 days intervals were adopted, assuming that the variation of the actions occurred in the middle of the interval, remaining constant in each interval. The structural analysis was carried out with output for every 5 intervals.

In order to quantify the impact of the swelling process on the structure, a structural analysis without the swelling action was also performed.

4.   RESULTS

4.1   Displacements

One of the consequences of the expansive reactions is the volumetric increase, which manifests itself through observable deformation.

The numerical results obtained from the time-analysis, with all actions (dead weight, hydrostatic and earth pressure, temperature variations and swelling), show that there is a considerable volumetric increase, namely, vertical blistering on the top and horizontal displacement at the middle level (Figure 4.1). Figure 4.2 shows deformation of the wall at several moments. Both figures include the corresponded deformations of the structure without effect of DEF.
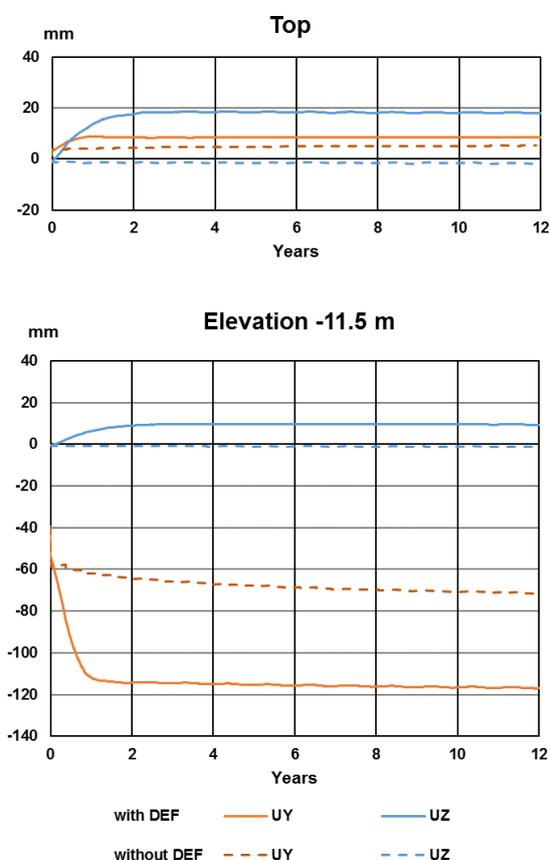

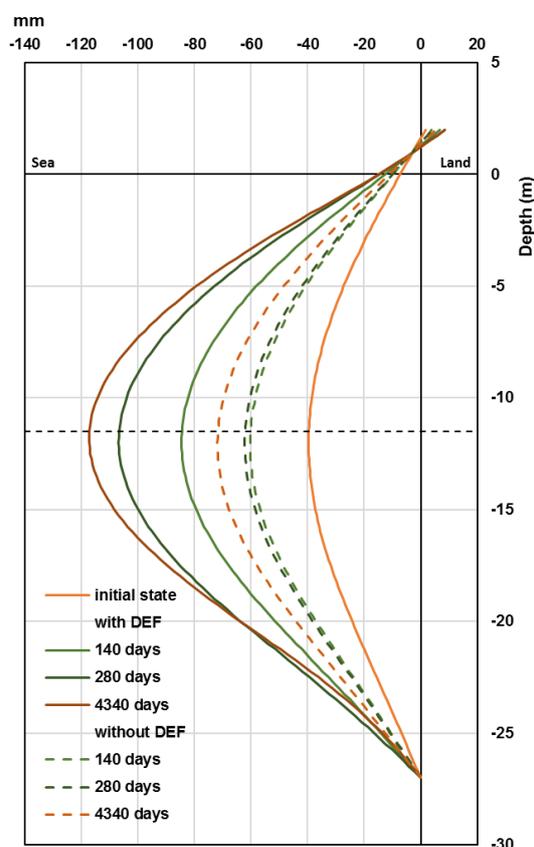Figure 4.1: Displacement of the wall on the top and at the middle level

Figure 4.2: Deformed wall

The effect of the DEF is considerable. The vertical blistering on the top of the wall with ISR origin, after 10 years, will be of about 18 mm, corresponding to an average strain of 630×10^{-6}. The deformation of the wall would increase, especially at the middle level.

4.2 Surface stress

In most area of the surface, the angle of the principal stresses is nearly to the horizontal direction X, perpendicular to the main rebar. Therefore, Figure 4.3 presents the stress distribution, σ_{xx}, at the Gauss points, close to the land and seaside surface of the wall.

As shown, there are extensive areas of the landside surface with tensile stresses, but the seaside surface is quite compressed. It is expected that the landside surface of the wall would be more cracked than the seaside. On the other hand, on both sides, at the upper and bottom areas the tensile stresses greater than 2 MPa are found.
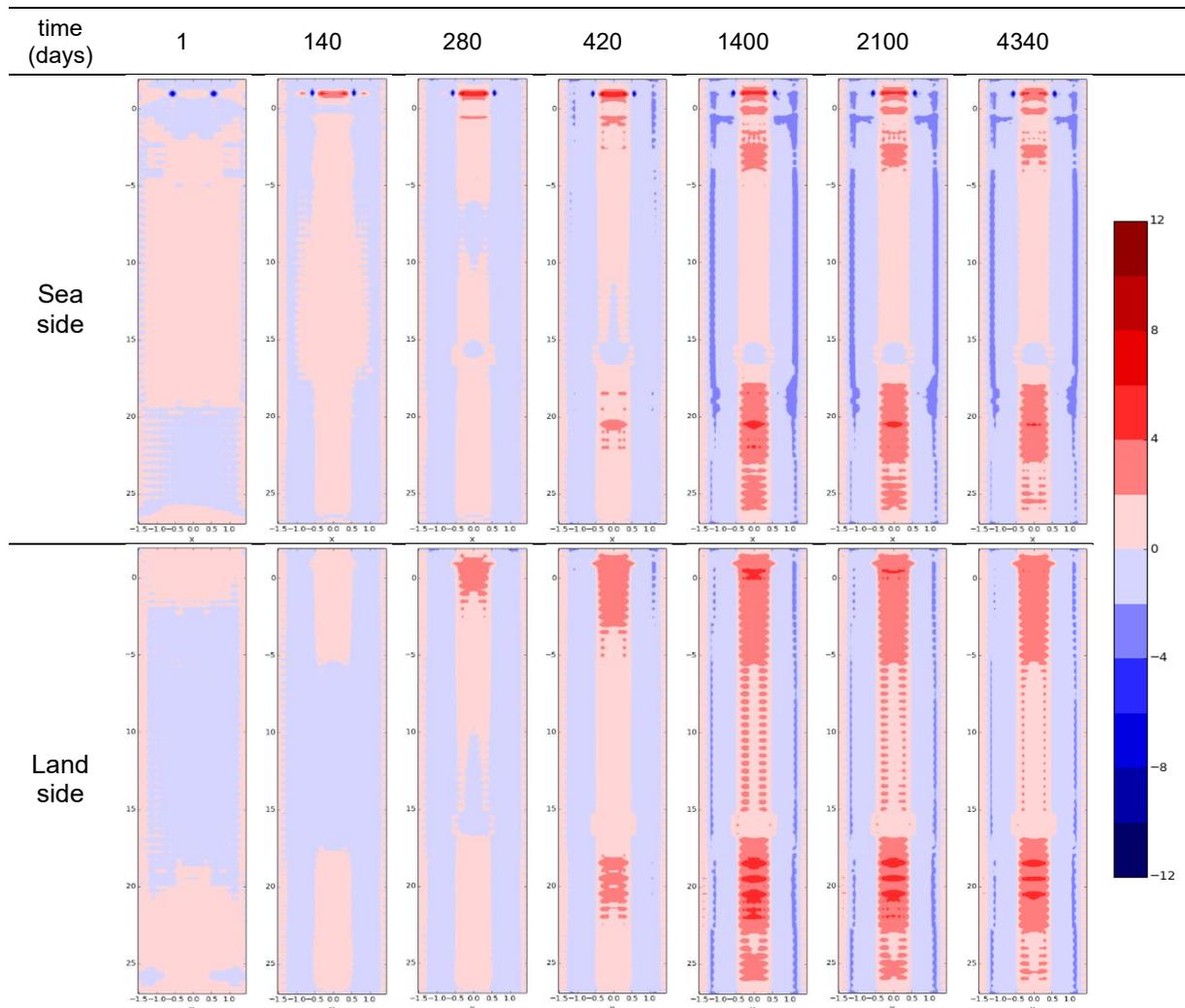

Figure 4.3: Surface stress σ_{xx} (MPa)

4.3 Rebar stresses

The rebar stresses were also analysed, as shown in Figure 4.4 and Figure 4.5. For the rebar class B 500S the characteristic yield strength is 500 MPa.

As can see in Figure 4.4, the vertical rebar, located near the seaside surface, are in tensile state, increasing up to 200 MPa. On the landside, the middle rebar is compressed, but the upper and lower

rebar are in tensile state. When the swelling progresses, the stress also increases, approaching the 400 MPa.

The swelling effect on the evolution of the tensile stress of the horizontal rebar is very clear (Figure 4.5). The stress increases with the expansion progresses, having a maximum value close to 480 MPa.
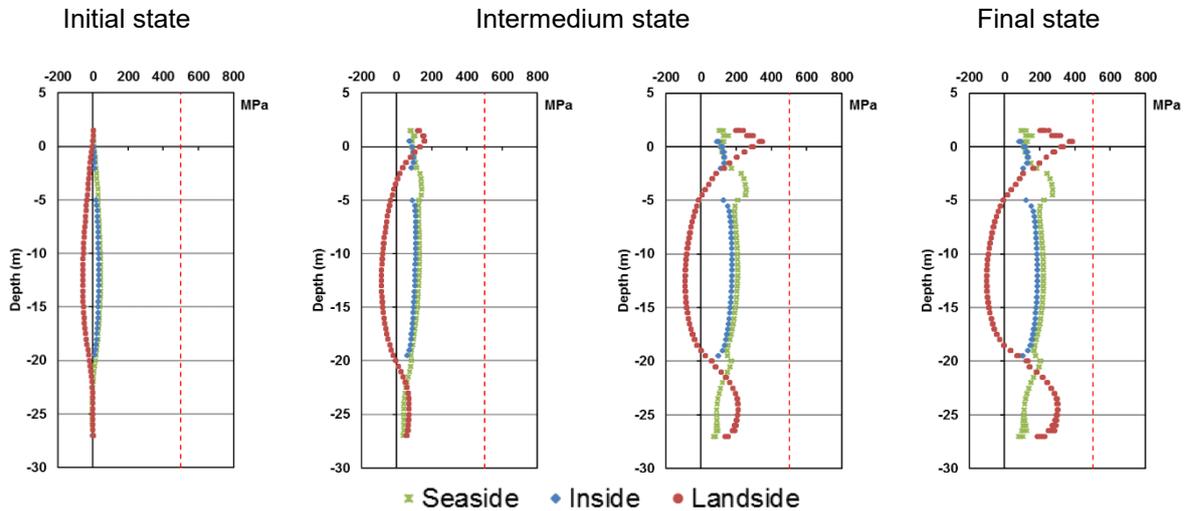

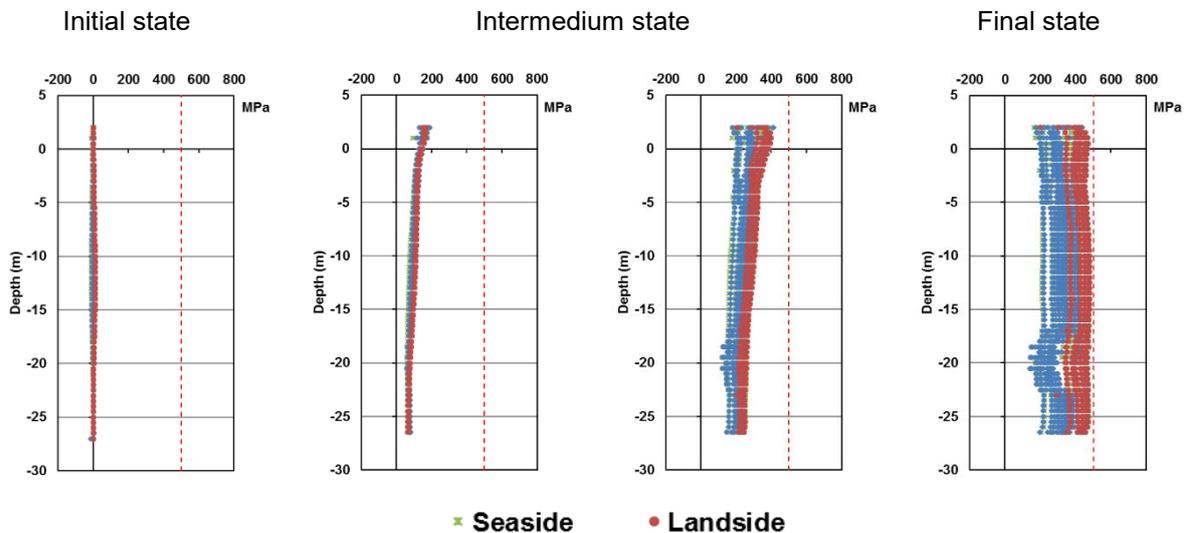Figure 4.4: Axial stress of vertical rebar (MPa)

Figure 4.5: Axial stress of horizontal rebar (stirrups) (MPa)

5. CONCLUSIONS

The paper presents the first approach for the swelling effect on the structure of the seaport, in order to obtain a general overview of the heterogeneous expansion development over time that is taking place inside the structure.

For the structural analysis the environmental thermal variations, as well as the water and earth pressure actions are considered. The free swelling action were estimated from the preliminary tests for the diagnosis of the swelling reactions. The modulus of elasticity and rheological behaviour of the concrete were considered using the EC2 predict model.

These numerical results, obtained in a viscoelastic regime, show an influence of the swelling effects on the structural behaviour. The structural deformation increases with the swelling evolution, which could be checked through observable deformation, as vertical displacement of the top of the wall. It is also

expected that the landside surface of the wall would be more cracked than the seaside. On both sides, the tensile stresses of the concrete greater than 2 MPa concentrate at the upper and bottom areas. At the same areas, the landside rebar also has high tensile stress, what indicate that are critical areas.

However, the structural modelling could be improved taking into account the results of expandability tests that could be carried out and supported by monitoring results. In further developments, the numerical modelling must also include the appearance and development of cracking due to swelling process.

6. ACKNOWLEDGEMENTS

7.   REFERENCES

[1] Taylor, H. F. W.; Famy, C. & Scrivener, K. L., "Delayed ettringite formation". Cement and Concrete Research, vol. 31, (5), pp. 683-693, 2001.

[2] Collepardi, M., "A state-of-the-art review on delayed ettringite attack on concrete". Cement and Concrete Composites, vol. 25, (4), pp. 401-407, 2003.

[3] Bardou, N., "Management of highway bridges affected by delayed ettringite formation pathology", in Encontro Nacional de Betão Estrutural - BE2018. LNEC, Lisboa, PT. 2018.

[4] CEN, "EN 1992 Eurocode 2. Design of concrete structures. 1.1 General rules. Structural fire design". European Committee for Standardization (CEN): Brussels, Belgium, 2004.

[5] Larive, C., Apports combinés de l'expérimentation et de la modélisation à la compréhension de l'Alcali-réaction et de ses effets mécaniques". PhD Thesis. École nationale de ponts e chaussées, Paris, France, 1998.

[6] Gomes, J.C.P., "Modelação do comportamento estrutural de barragens de betão sujeitas a reacções expansivas (Structural behavior modeling of concrete dams subject to swelling reactions)", PhD Thesis, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa (FCT/UNL) & Laboratório Nacional de Engenharia Civil (LNEC), Lisbon, 2008.

[7] MALBOIS, M., "Multi-scale analysis of delayed deformations in cement-based materials submitted to drying or delayed ettringite formation", PhD Thesis, Université Paris-Saclay, 2019.

[8] Brunetaud, X., "Étude de l'influence de différents paramètres et de leurs interactions sur la cinétique de l'amplitude de la réaction sulfatique interne au béton", Ecole centrale de Paris: Châtenay-Malabry, 2005.

[9] Baghdadi, N., "Modélisation du couplage chimico-mécanique d'un béton atteint d'une réaction sulfatique interne", PhD Thesis, Université Paris Est: Paris, 2008.

[10] Martin, R. P., "Analyse sur structures modèles des effets mécaniques de la réaction sulfatique interne du béton", PhD Thésis, Université Paris-Est, 2010.

[11] Malbois, M., "Analyse multi-echelle des déformations différées dans les matériaux cimentaires sous dessiccation ou réaction sulfatique interne", PhD Thesis, Université Paris-Saclay, 2019.

[12] Gomes, J.C.P; Batista, A. L.; Oliveira, S.B., "Damage-chemo-viscoelastic model on the analysis of concrete dams under swelling processes", in 2nd International Conference on Long Term Behaviour of Dams, LTBD09. Graz, Austria, 2009.